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AN AERODYNAMIC ASSESSMENT OF VARIOUS SUPERSONIC FIGHTER AIRPLANES BASED ON SOVIET DESIGN CONCEPTS

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SUMMARY

The aerodynamic, stability, and control characteristics of several supersonic fighter airplane concepts have been assessed. The configurations, which are based on Soviet design concepts, include fixed-wing airplanes having delta wings, swept wings, and trapezoidal wings, and variable wing-sweep airplanes. Each concept employs aft tail controls. The concepts vary from lightweight, single engine, air superiority, point interceptor, or ground attack types to larger twin-engine interceptor and reconnaissance designs. Analytical and experimental results indicate that careful application of the transonic or supersonic area rule can provide nearly optimum shaping for minimum drag for a specified Mach number requirement. In addition, through the proper location of components and the exploitation of interference flow fields, the concepts provide linear pitching moment characteristics, high control effectiveness, and reasonably small variations in aerodynamic center location with a resulting high potential for maneuvering capability. The lateral-directional characteristics also indicate that by careful attention to component shaping and location and through the exploitation of local flow fields, favorable roll-to-yaw ratios may result and a high degree of directional stability can be achieved.

INTRODUCTION

A continual interest exists in examining and updating the state-of-the-art in fighter airplane concepts. Soviet fighters provide a good basis for the study of supersonic design concepts because of the wide variety of fielded types covering a broad spectrum of possible mission requirements. These mission requirements include air superiority, ground attack, close air support and battlefield interdiction, air intercept, and reconnaissance. Airplanes in use for these various missions vary from lightweight single-engine fighters to relatively heavy twin-engine fighters. The configurations include fixed-wing airplanes having delta wings (representative of Fishbed, Flagon, and Fishpot), swept wings (representative of Fitter A), trapezoidal wings (representative of Foxbat), and variable-sweep-wing airplanes (representative of Fitter C, Fencer, and Flogger). Each of the configurations have aft-tail controls. The approach will be to review the results of analytical studies as well as experimental wind tunnel verification studies of simulated models of the concepts. The aerodynamic, stability, and control characteristics determined from these studies will be used in an attempt to assess the relative merits of the concepts. Some observations will also be made concerning possible future trends in fighter concepts.

SYMBOLS

The longitudinal results are referred to the stability axis system and the lateral results are referred to the body axis system. The coefficients, symbols, and abbreviations are defined as follows:

a_n	instantaneous normal acceleration in g units
b	wing span
$\bar{c}$	wing mean aerodynamic chord
$C_{D,wave}$	supersonic wave drag coefficient, $\frac{\text{wave drag}}{qS}$
C_ℓ	rolling-moment coefficient, $\frac{\text{rolling moment}}{qSb}$
C_{ℓ_β}	effective dihedral parameter, per degree
$C_{\ell_{\beta_\alpha}}$	variation of effective dihedral with angle of attack near $\alpha = 0°$
C_L	lift coefficient, $\frac{\text{lift}}{qS}$
C_m	pitching-moment coefficient, $\frac{\text{pitching moment}}{qS\bar{c}}$
$\frac{\partial C_m}{\partial C_L}$	longitudinal stability parameter
C_n	yawing-moment coefficient, $\frac{\text{yawing moment}}{qSb}$
C_{n_β}	directional stability parameter, per degree
h	altitude
L/D,max	maximum lift-drag ratio
M	free-stream Mach number
q	free-stream dynamic pressure
s.m.	static margin, percent $\bar{c}$
S	reference wing area including fuselage intercept
W	weight
W/S	wing loading
α	angle of attack, degrees

β angle of sideslip, degrees

δ_h horizontal tail deflection (positive trailing edge down), degrees

Λ leading-edge sweep angle, degrees

Model components:

V vertical tail

U ventral fin

T wing tip fin

MODELS

The configuration concepts included in the present study are shown in figures 1 to 4. The geometric shapes were simulated from the best available open source characteristics, photographs, and drawings. This information was used in conjunction with computer-aided design techniques to develop the more detailed cross-sectional shapes that would result in configurations that would meet the expected performance requirements within the bounds of the geometric constraints. The configurations having nose inlets were designed with faired-over inlets which, when properly done, has little effect on the external aerodynamics. The simulated Foxbat, which has horizontal-ramp, twin side inlets, was designed as a flow-through model with provisions for correcting for the internal flow. An example of the type of computer-aided design process is illustrated in figure 5 by the drawing of the numerical model of the trapezoid wing model (simulated Foxbat). Such drawings are used in the determination of the analytical aerodynamic characteristics of the configurations and are also used in the construction of models for wind-tunnel testing to provide data for verification of the analytical results.

DISCUSSION

Longitudinal Aerodynamic Characteristics

Wave drag calculations.- Some examples of the application of analytical techniques are shown in figures 6 to 8. In figure 6, the area distribution for the original delta-wing model (simulated Fishbed) is shown as the solid line. The wave drag calculations for this area distribution indicated that the shape was optimized for minimum wave drag at $M = 1.5$. Calculations were made to determine the area distribution necessary for minimum wave drag at $M = 1.2$. The results, shown by the dashed line in figure 6, primarily indicated that the addition of volume aft of the canopy would be desirable in order to make a more parabolic area distribution. The wave drag calculations for these shapes (fig. 7) indicate that the optimum drag for the original shape does occur at $M = 1.5$ with an increase in drag for either higher or lower supersonic Mach numbers. The modified shape with the added volume resulted in a 20-percent reduction in wave drag at $M = 1.2$ with no drag penalty up to the limit speed of $M = 2$. For a better perspective of the effect of this modification, the reduction in wave drag is the equivalent to about a 10-percent reduction in total drag which corresponds to about a 100 knot increase in speed for an airplane the size of a Fishbed. This improvement was accomplished by smoothing the area distribution through the addition of volume to the back of the body--a modification that has become noticeable on more recent versions of the Fishbed fighter. An additional curve shown in figure 7 indicates the lower bound of wave drag possible at each Mach number through optimum shaping (i.e., a "rubber" airplane). It is interesting to note that the lower bound was achieved at $M = 1.2$, and at the higher Mach numbers, the lower bound is not drastically less than the actual wave drag level for the airplane.

A comparison of the calculated wave drag for the delta wing fighter and the trapezoidal wing fighter is shown in figure 8. Trade study calculations were originally made for the trapezoidal wing fighter (simulated Foxbat) with wing thickness ratios of 3, 4, and 5 percent. However, it was found that the 3 percent wing, while easily meeting the $M = 3$ drag requirements for Foxbat, could not be built to contain fuel. The 5-percent wing provided ample volume for fuel but produced a level of wave drag inconsistent with $M = 3$ flight. The 4-percent wing evolved as being suitable both for the $M = 3$ drag criteria and for a wet-wing structure and was used in the subsequent studies. At the lower Mach numbers, the wave drag for the configurations are comparable but the significant effect is that the wave drag for the trapezoid configuration decreases with increasing Mach number and tends to become optimum near $M = 3$. In fact, for $M = 2$, the wave drag of the trapezoid configuration is about one-third less than that for the apparently more slender delta-wing fighter. Some of the reasons for this lower wave drag are indicated in the comparison of equivalent body area distributions for $M = 2.0$ as calculated by means of the supersonic area rule. Three advantageous features are indicated for the trapezoid configuration: (1) a lower forebody slope, (2) a lower peak value, and (3) a slightly lower afterbody closure.

<u>Longitudinal stability and maneuverability</u>.- Some experimentally determined longitudinal stability and control characteristics for the trapezoid wing fighter (fig. 9) indicate a reasonably small variation of stability level over the Mach number range from $M = 0.6$ to about $M = 3.3$. The results for $M = 2.86$ show a linear variation of pitching moment with lift and good control effectiveness. Accordingly, the potential maneuvering capability is substantial as indicated for the assumed conditions at 20 km altitude with fuel nearly expended. The static margin of 20 percent $\bar{c}$ corresponds closely to a takeoff center-of-gravity location, and reductions in static margin of 5 to 10 percent are not unreasonable if proper fuel management is employed to shift the center of gravity. Somewhat greater maneuver potential is shown for $M = 3.3$ (fig. 10) due to the combined effects of a lower static margin, higher flight dynamic pressure, and an increase in control effectiveness with increasing C_L (or α) as a result of increased local dynamic pressure induced at the tail by the flow field of the wing.

Some maneuver bounds for a swept-wing fighter are shown in figure 11 as a function of stability level for various altitudes that encompass the air superiority and air intercept regions. Suffice it to say that, because of linear pitching moment curves and good control effectiveness, the configuration is potentially able to reach the probable load limit of the structure or the tolerance level of the pilot, particularly at the lower altitudes.

Characteristics of the variable sweep wing concept are illustrated in figure 12. The variation of stability level with wing sweep at subsonic speeds ($M = 0.5$) and the variation with M for the fully swept wing are relatively small--both being factors that would enhance the maneuvering potential. The advantages of the variable wing sweep in varying the lift and drag are self evident and can be exploited to influence range, speed, maneuverability (turn radius), the overall operating envelope, and the flight handling qualities.

Lateral-Directional Aerodynamic Characteristics

The lateral-directional characteristics illustrate strong effects of configuration geometry and of interference flow fields. In figures 13 to 15, for example, the variation of effective dihedral with angle of attack, $C_{\ell_{\beta_\alpha}}$, is shown as a function of Mach number for each of the wing concepts in the low α range. Theoretically, this parameter changes from a negative value to nearly zero or slightly positive values when the wing leading edge becomes sonic. This condition occurs almost exactly for the delta-wing fighter (fig. 13) and for the 63-degree swept-wing fighter (fig. 14). The effective dihedral is quite dependent on planform, generally having more negative values as the sweep angle increases. This change in magnitude is apparent in these results with somewhat lower values being obtained with the 45 degree variable sweep panel (fig. 14) and for the lower sweep trapezoidal wing (fig. 15). The condition of nearly zero values of $C_{\ell_{\beta_\alpha}}$ for the sonic wing is evident for each of the planforms, thus a favorable reduction in the roll-to-yaw ratio may result.

The directional stability characteristics of the trapezoidal wing fighter are illustrated on figure 16 for several geometric modifications (fig. 4) at supersonic Mach numbers of 2.5 and 4.6. The basic configuration with twin-vertical tails (V) becomes directionally unstable near $\alpha = 8°$ for $M = 2.5$ and was completely unstable at $M = 4.6$. The addition of twin ventral fins (VU), in a region of high local dynamic pressure, provided directional stability up to about $\alpha = 20°$ at $M = 2.5$ but had little beneficial effect at $M = 4.6$ because of the attendant decrease in effectiveness of the basic vertical tail with increasing M. However, the addition of twin wing tip fins (VUT) resulted in a substantial increment in directional stability at $M = 2.5$ and this increment was maintained at $M = 4.6$ so that positive directional stability was available at angles of attack up to at least 22 degrees.

Trends

In a 1967 airshow, the Soviets displayed various new fighter concepts to the western world for the first time. Among these was the fixed-wing, twin-engine, M = 3 Foxbat for high-speed, high-altitude, interceptor and reconnaissance missions--a fighter in a class to itself. Also introduced was the delta wing, twin-engine, M = 2.5 Flagon interceptor. Both of these fighters demonstrated the Soviet interest in the advancement of high performance fighters and both have long been in the inventory in quantity. Continued Soviet interest in advanced supersonic fighters was evident by the early 1980's with the introduction of the Foxhound, Fulcrum, and Flanker. In addition, the subsonic Frogfoot was also introduced. Soviet interest in V/STOL airplanes was also displayed in the 1967 airshow with variable wing-sweep designs as well as with various lift-engine concepts. Variable sweep was demonstrated on a modified Fitter, using an outboard wing pivot, and on the newly designed single-engine Flogger using an inboard pivot. Both of these airplanes have since entered the inventory in large numbers. Continued interest in variable sweep has been shown by the subsequent introduction of the two-seater Flogger C; the two-seater, twin-engine Fencer ground-attack fighter; and the Backfire and Blackjack bombers. The lift-engine concepts shown in 1967 were the newly designed Faithless, a modified Flagon, a modified Fishbed, and a vectored-thrust concept, the Freehand. None of these airplanes entered the inventory, however, the exploitation of these designs emerged in 1976 when the Forger VTOL fighter, employing both lift engines and vectored thrust, was deployed on the Soviet Navy carrier Kiev.

Based upon the open literature, a considerable Soviet effort in high speed aerodynamics and propulsion continues. In the September 11, 1970 issue of Red Star, I. I. Anureyev, a Doctor of Military Sciences, Professor, and Major General of the Engineering and Technical Services was quoted: "Aerodynamic craft have achieved high tactical properties. The maximum flight speed of a plane is approximately 3,000 kilometers per hour (M = 2.8) and the practical ceiling is 30 kilometers (100,000 ft.), and this is not the limit. The most immediate prospect for aerodynamic apparatuses is to attain hypersonic speeds, that is, speeds approximately five times as fast as the speed of sound."

An artist concept that accompanied the article is shown schematically in figure 17. The drawing depicts some features that could be expected on the type of fighter to which the quote alludes. There is evidence of an airbreathing, scramjet-type propulsion system utilizing the under surface of the body and a blended, straked wing as a compression surface. Two-dimensional nozzle technology could also be incorporated. Twin vertical and ventral fins are depicted as well as wing-tip fins that would probably be required to provide adequate directional stability for near M = 5 flight. The technology is available, the systematic groundwork has been laid, it remains to be seen if the Soviets will follow through.

CONCLUDING REMARKS

An aerodynamic assessment has been made of the characteristics of several supersonic fighter airplane concepts. The configurations, which are based on Soviet design concepts, include fixed-wing airplanes having delta wings, swept wings, and trapezoidal wings, and variable wing-sweep airplanes. Each concept had aft-tail controls. The concepts vary from lightweight, single engine, air superiority, point interceptor, or ground attack types to larger twin-engine interceptor and reconnaissance designs. Analytical and experimental results indicate that careful application of the transonic or supersonic area rule can provide nearly optimum shaping for minimum drag for a specified Mach number requirement. In addition, through the proper location of components and the exploitation of interference flow fields, the concepts provide linear pitching moment characteristics, high control effectiveness, and reasonably small variations in aerodynamic center location with a resulting high potential for maneuvering capability. The lateral-directional characteristics also indicate that by careful attention to component shaping and location, and through the exploitation of local flow fields, favorable roll-to-yaw ratios may result, and a high degree of directional stability can be achieved.

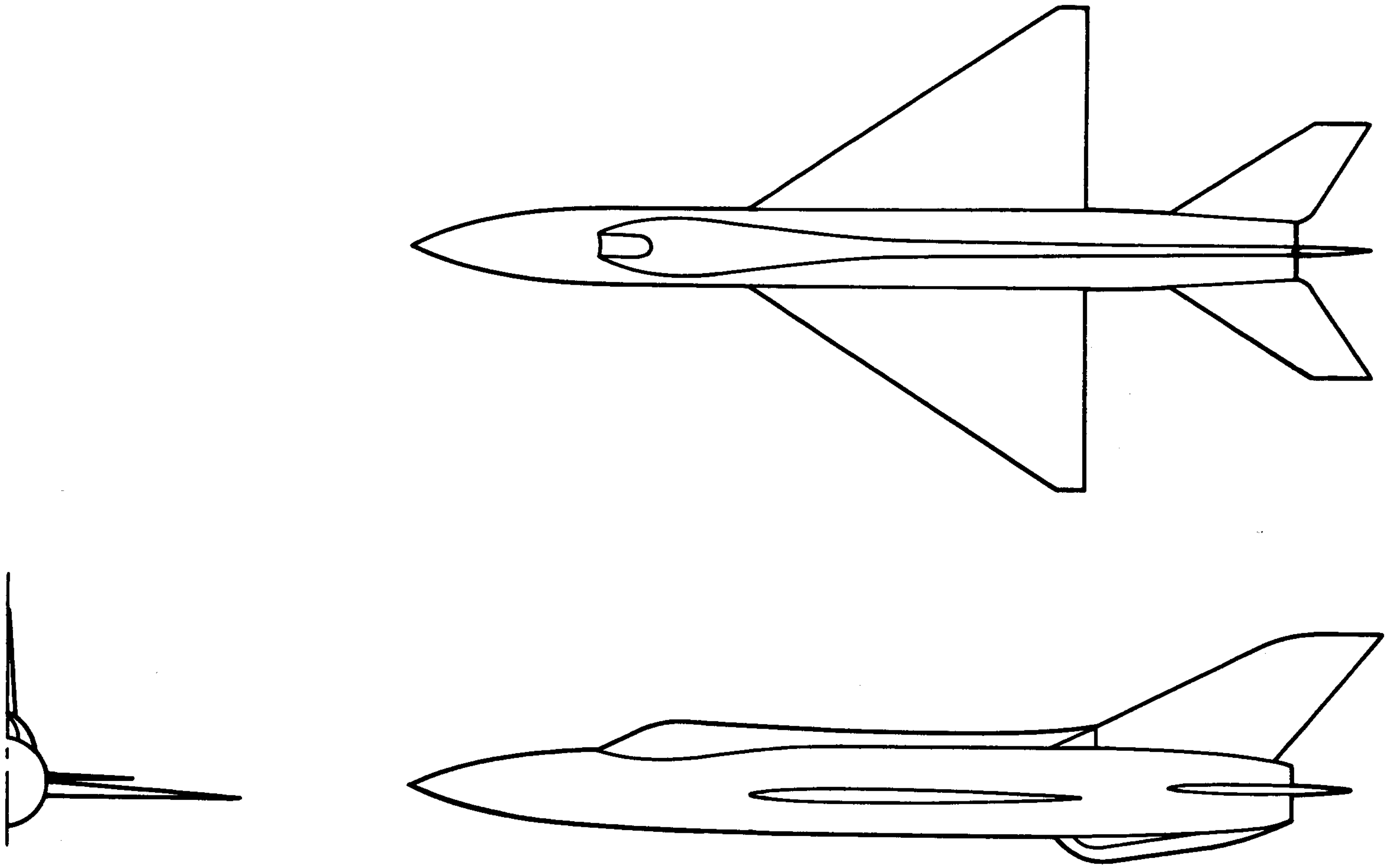


Figure 1.- Delta wing fighter.

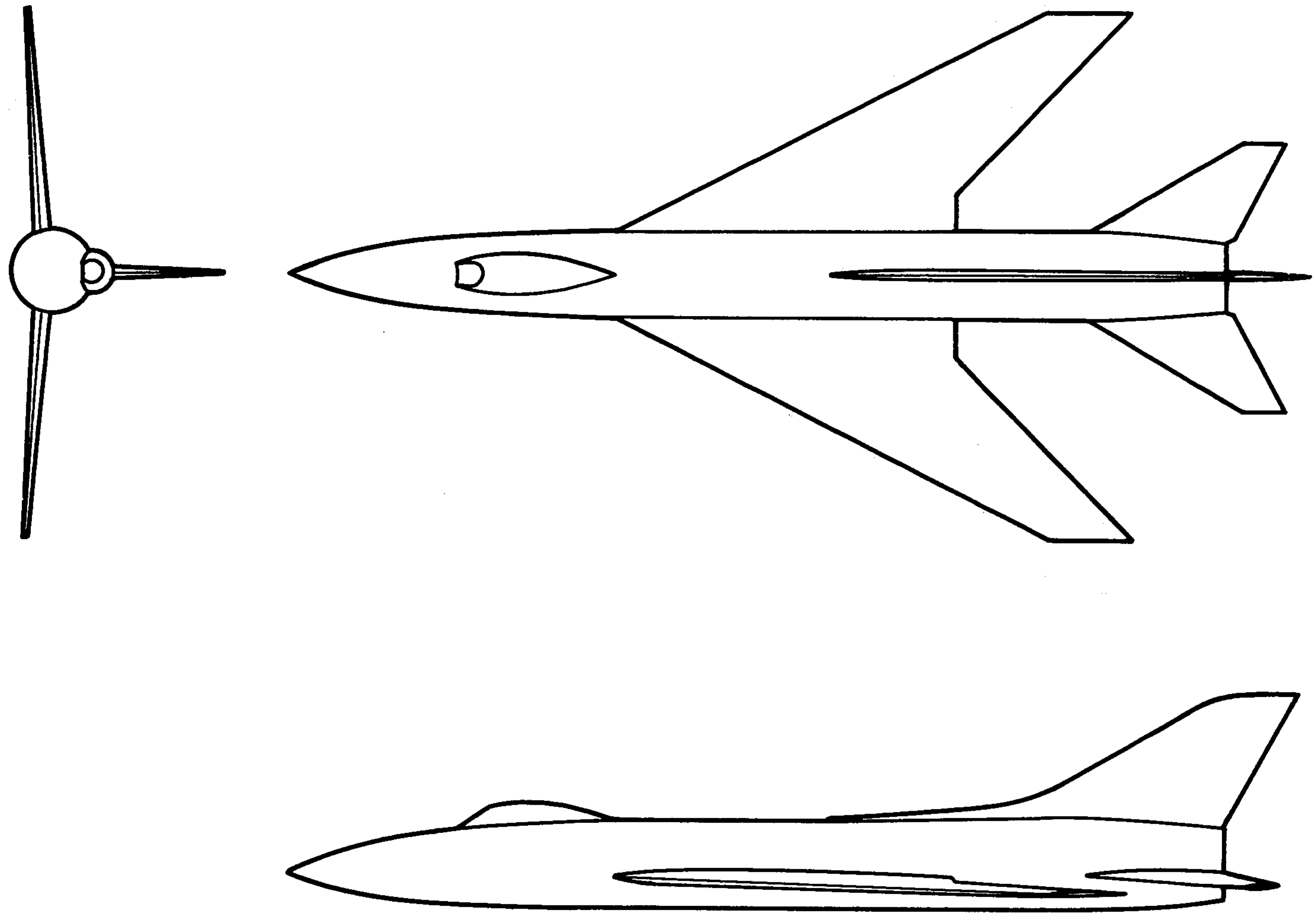


Figure 2.- Swept wing fighter.

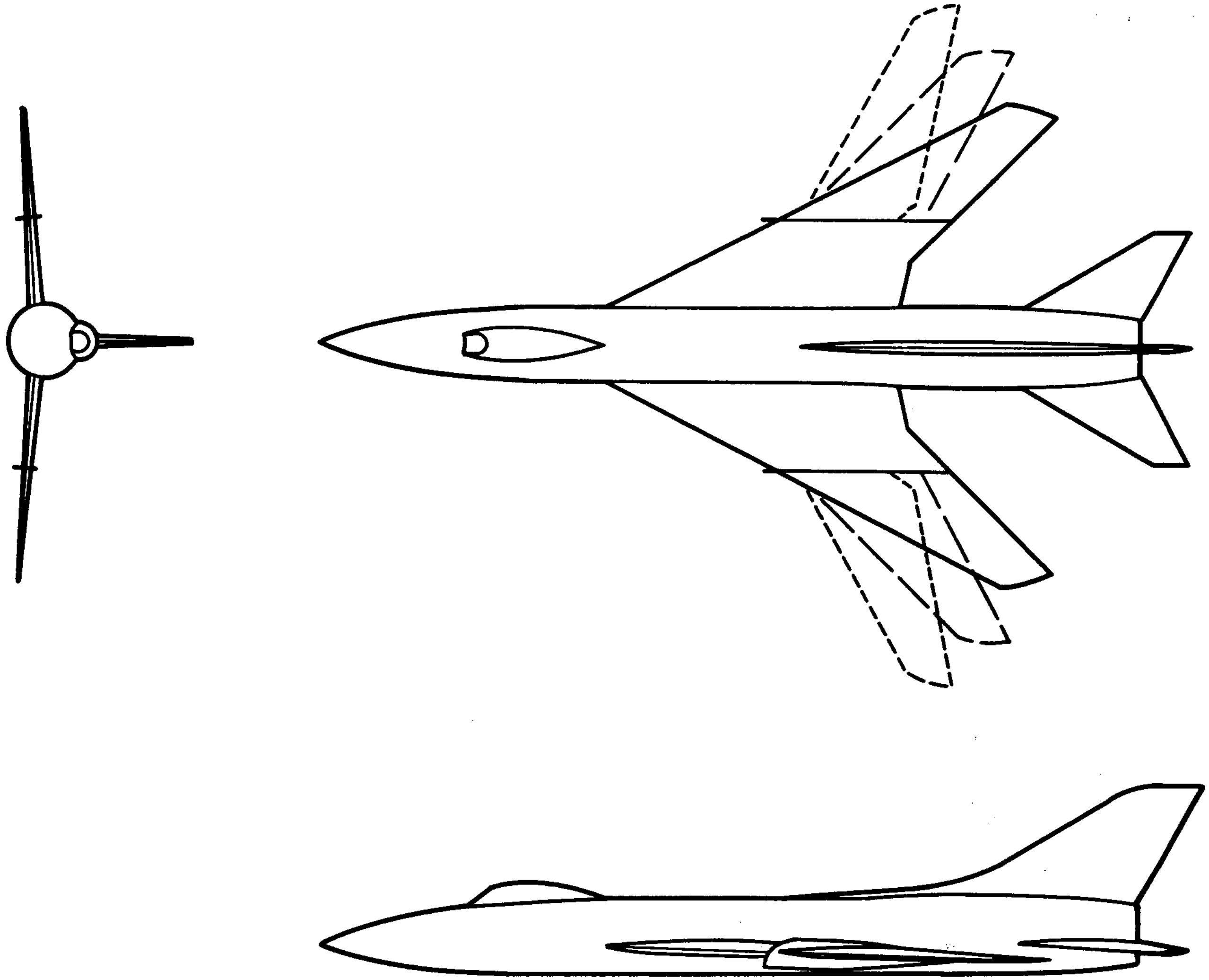


Figure 3.- Variable-sweep wing fighter.

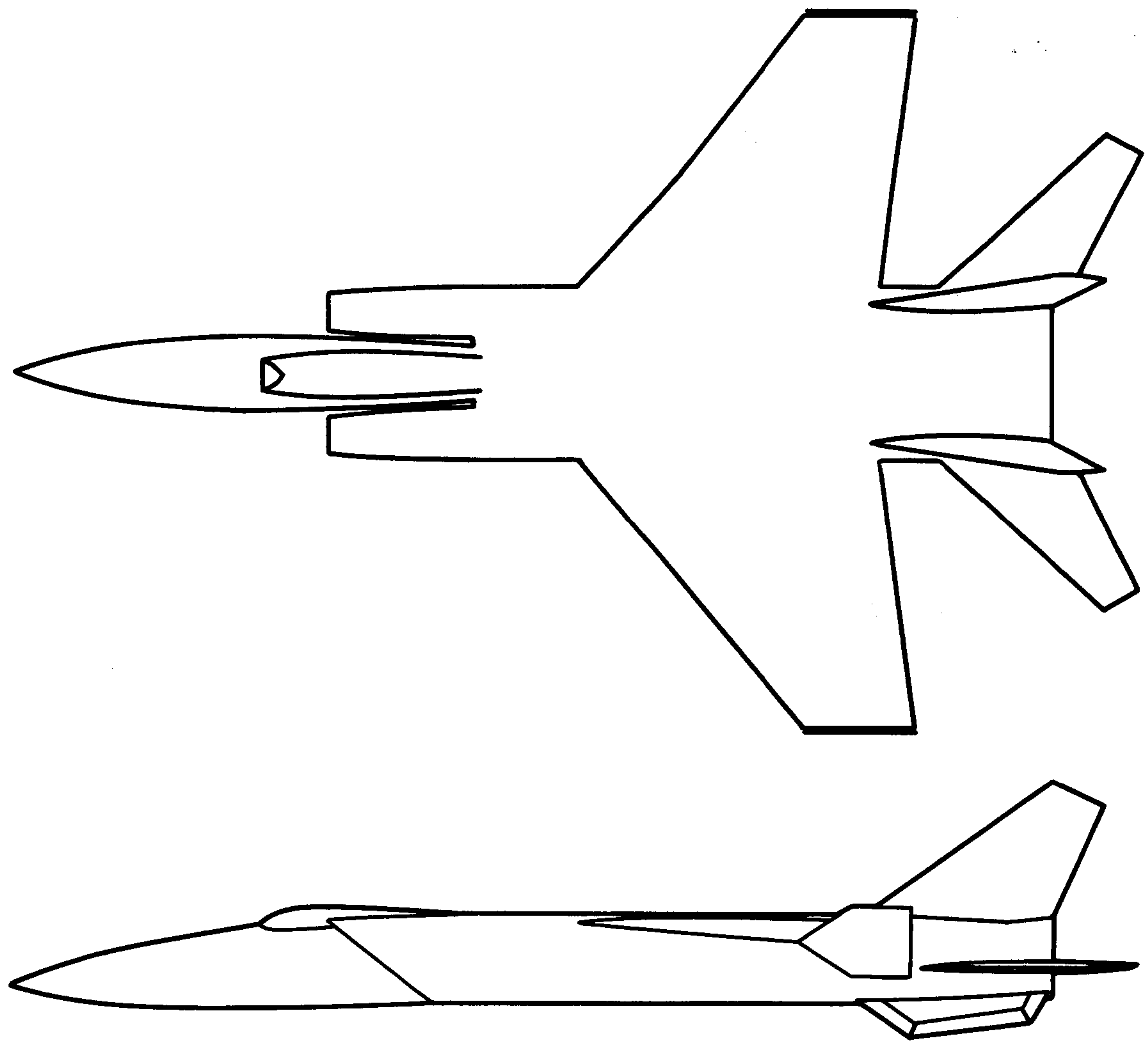


Figure 4.- Trapezoidal wing fighter.

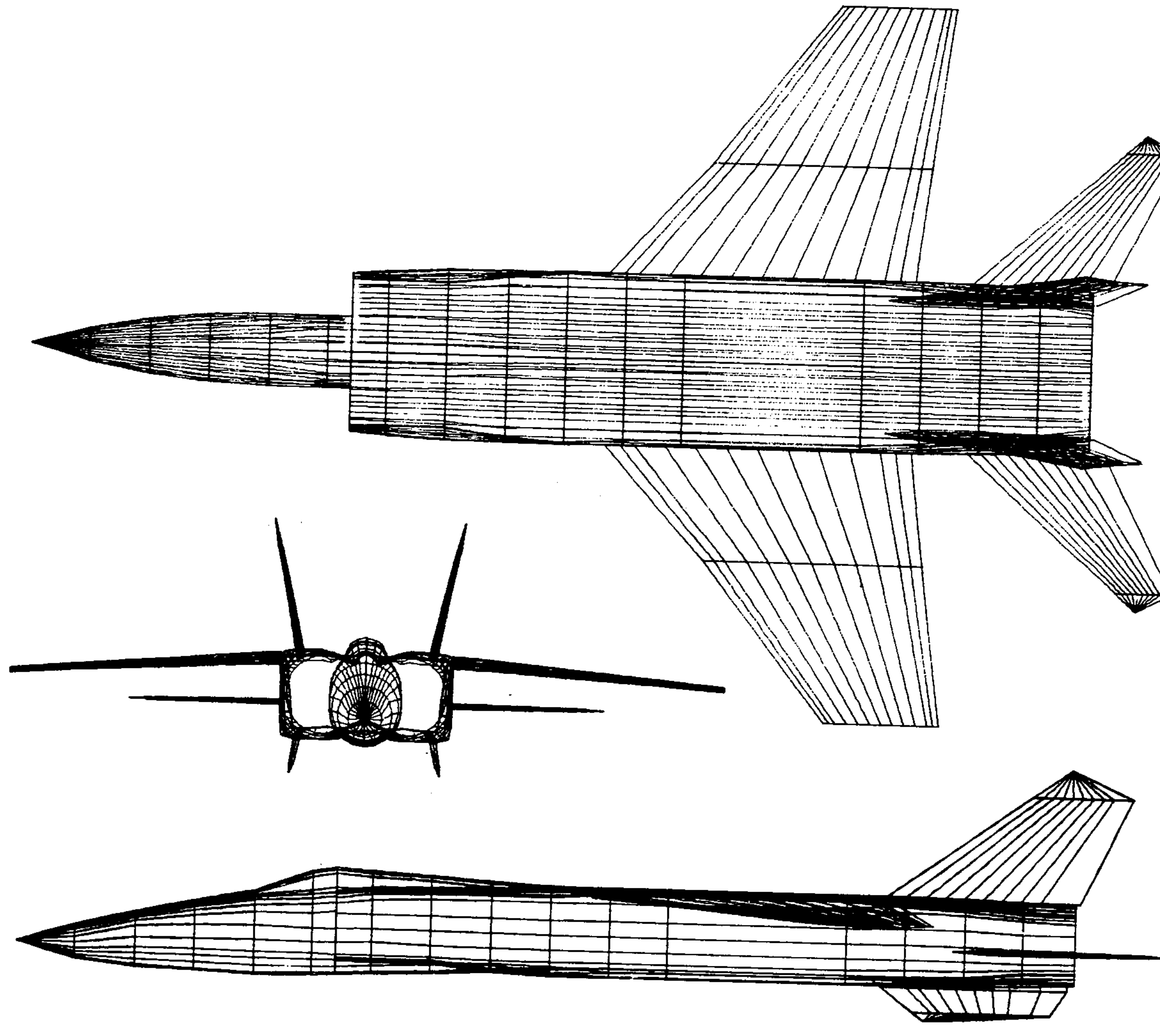


Figure 5.- Computer drawing of numerical model.

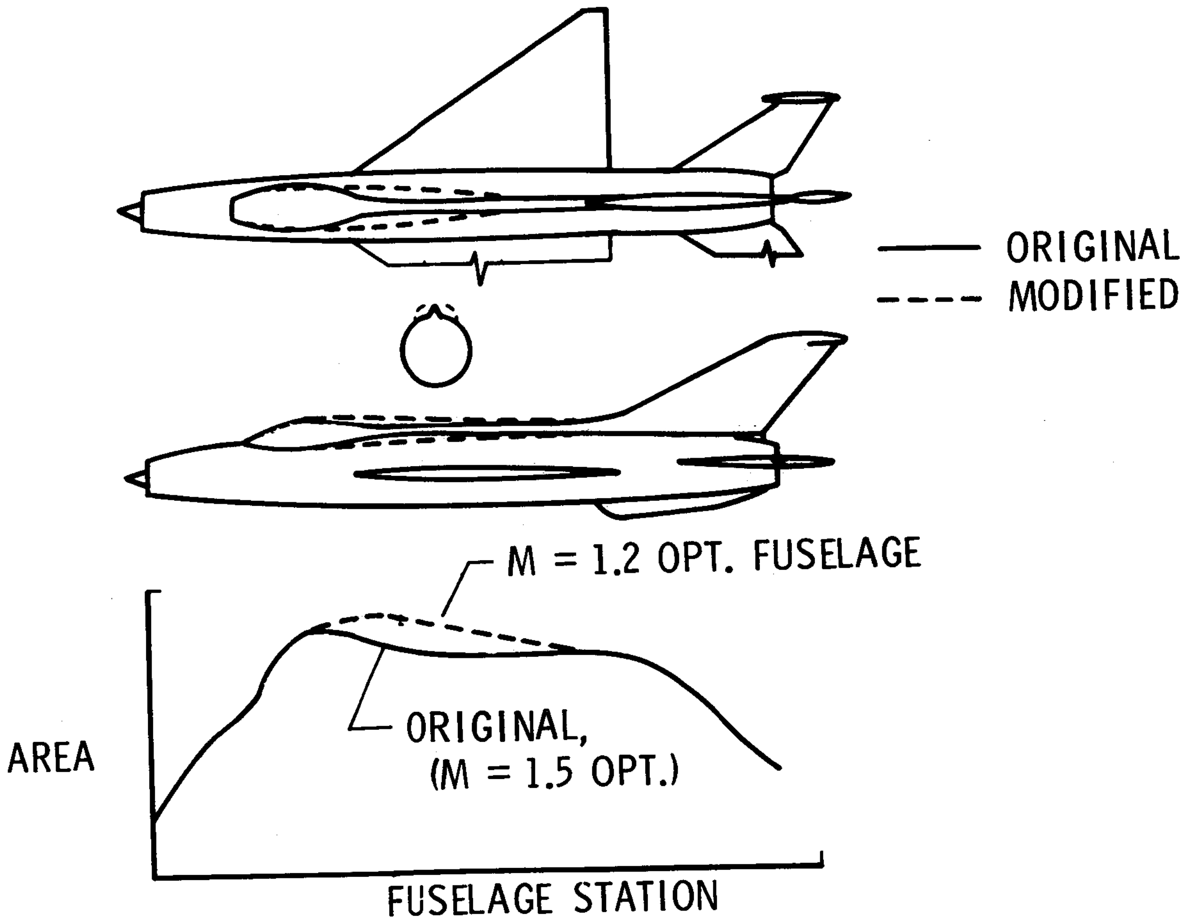


Figure 6.- Delta wing fighter area distributions.

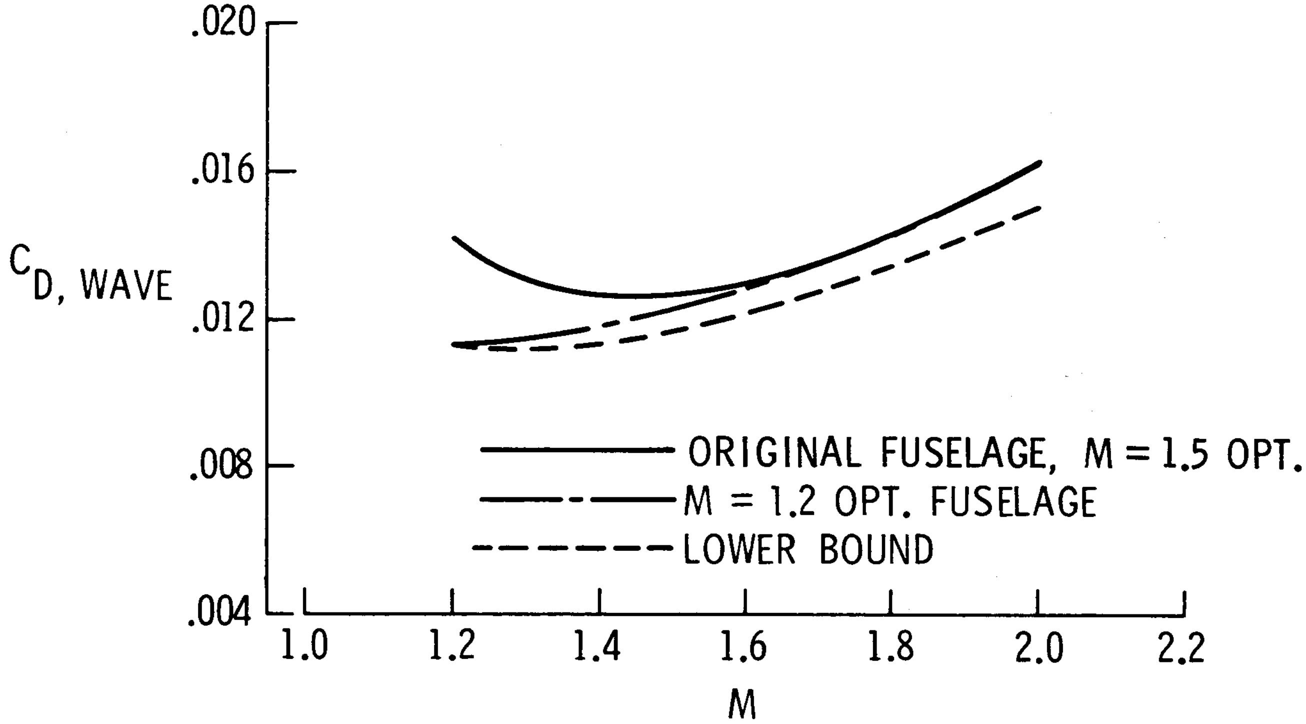


Figure 7.- Delta wing fighter wave drag.

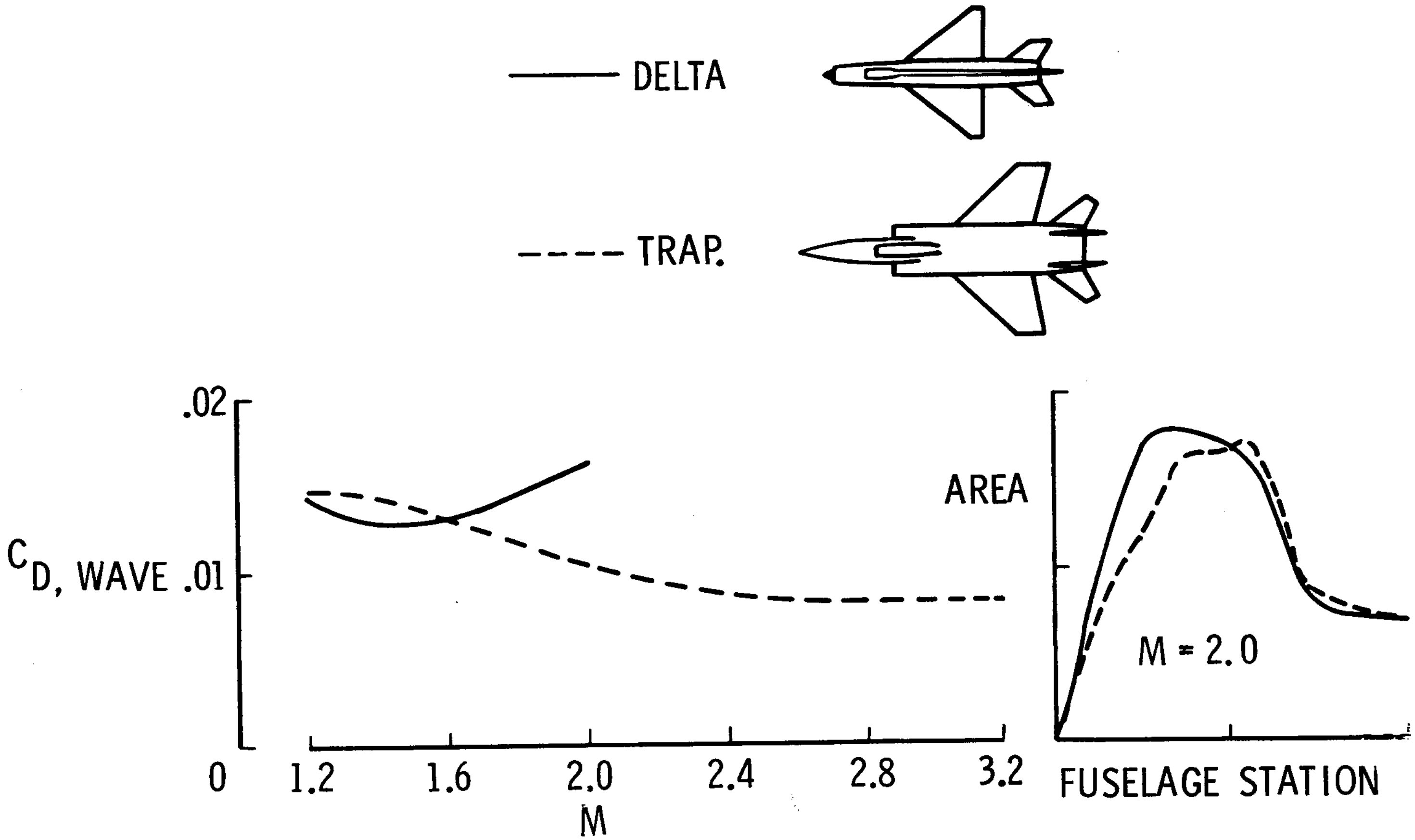


Figure 8.- Wave drag comparison, delta and trapezoid wing fighters.

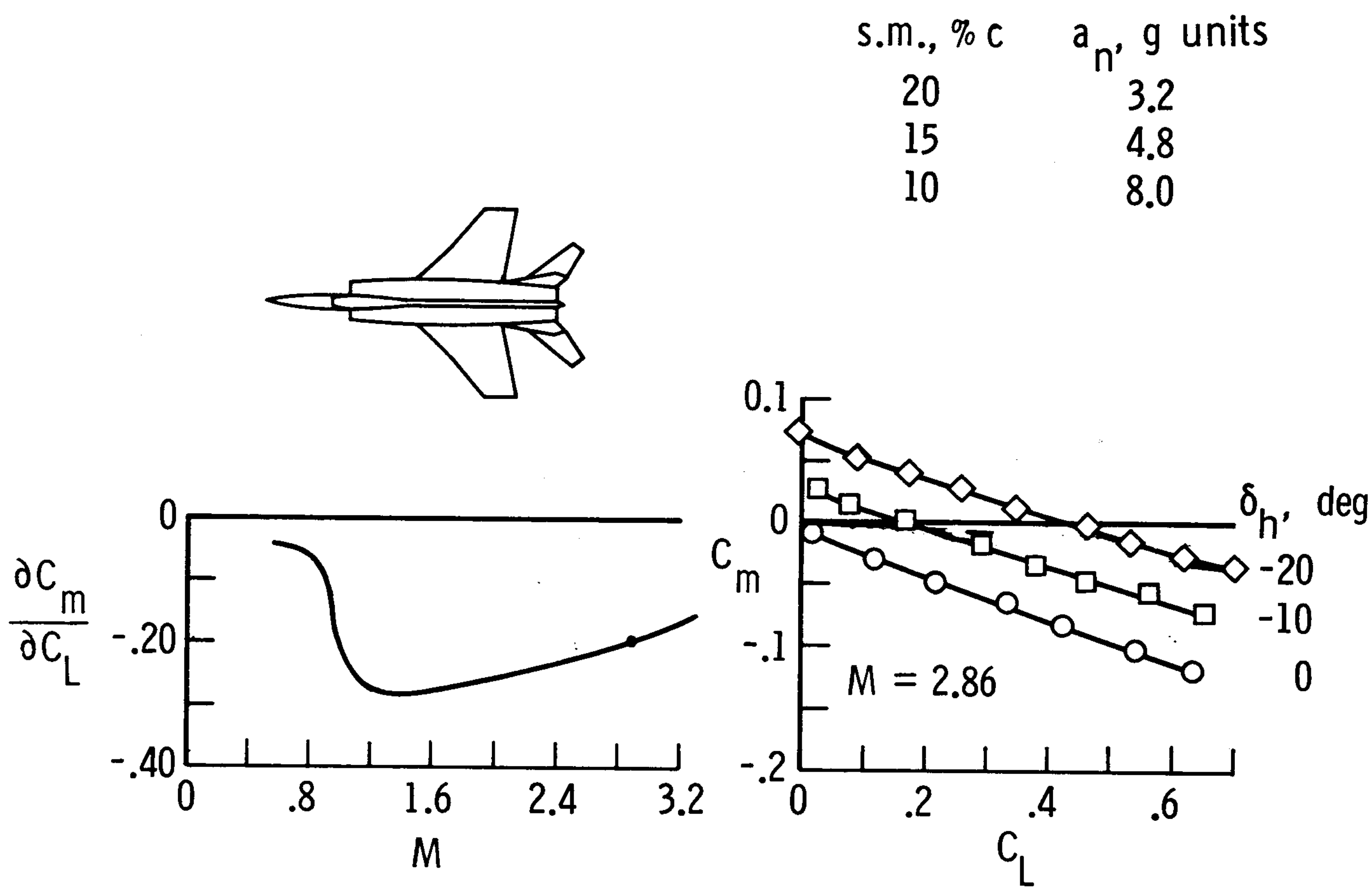


Figure 9.- Longitudinal characteristics, trapezoid wing fighter.

W/S =65 psf , h = 65,000 ft.

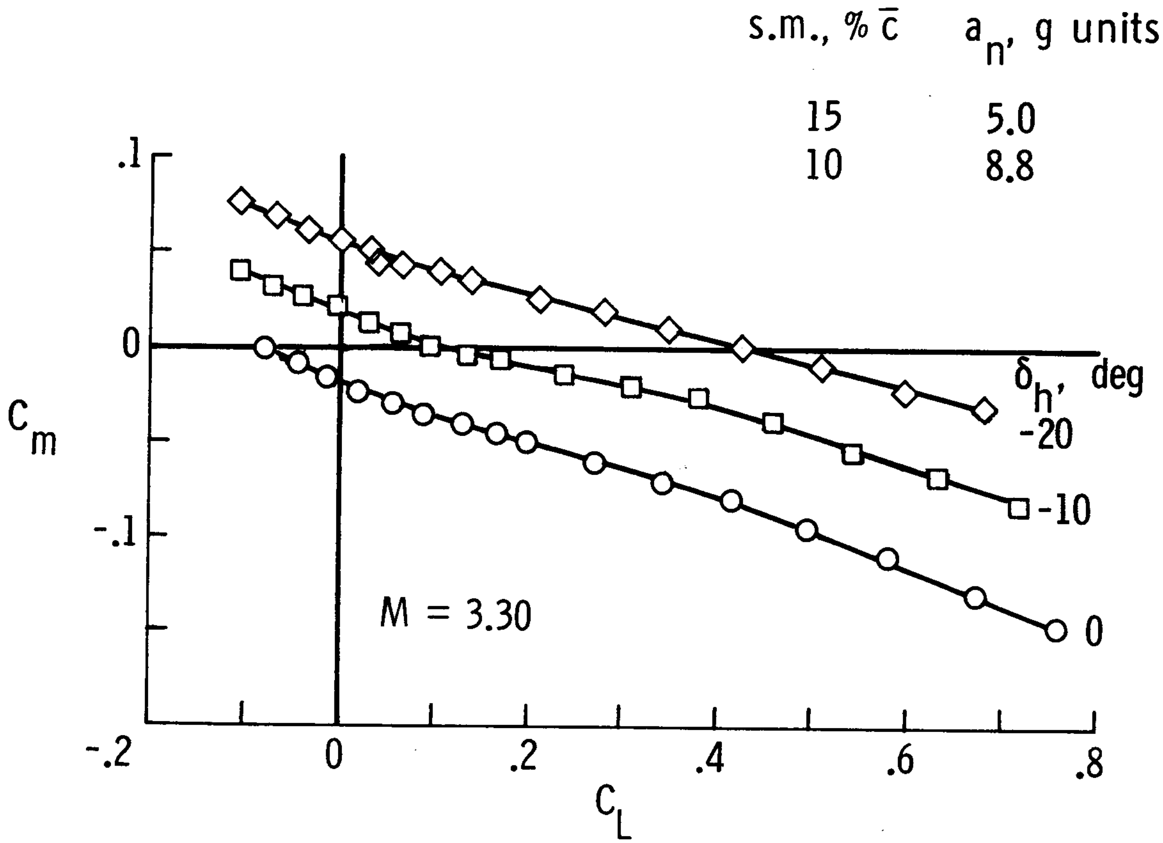


Figure 10.- Trapezoid wing fighter characteristics, M = 3.30.

W/S = 65 psf , h = 65,000 ft.

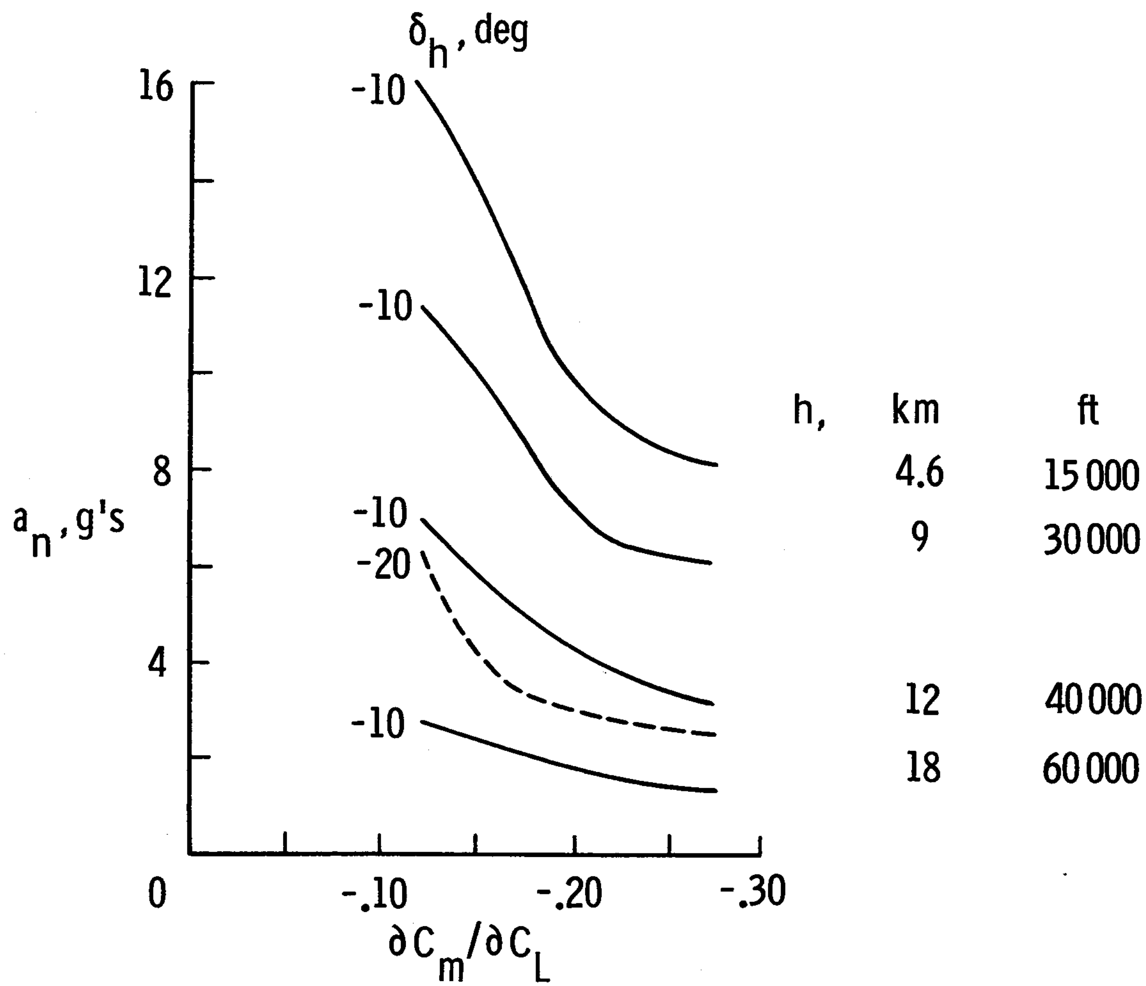


Figure 11.- Swept wing fighter maneuver bounds, M = 2.0. W/S = 65 psf

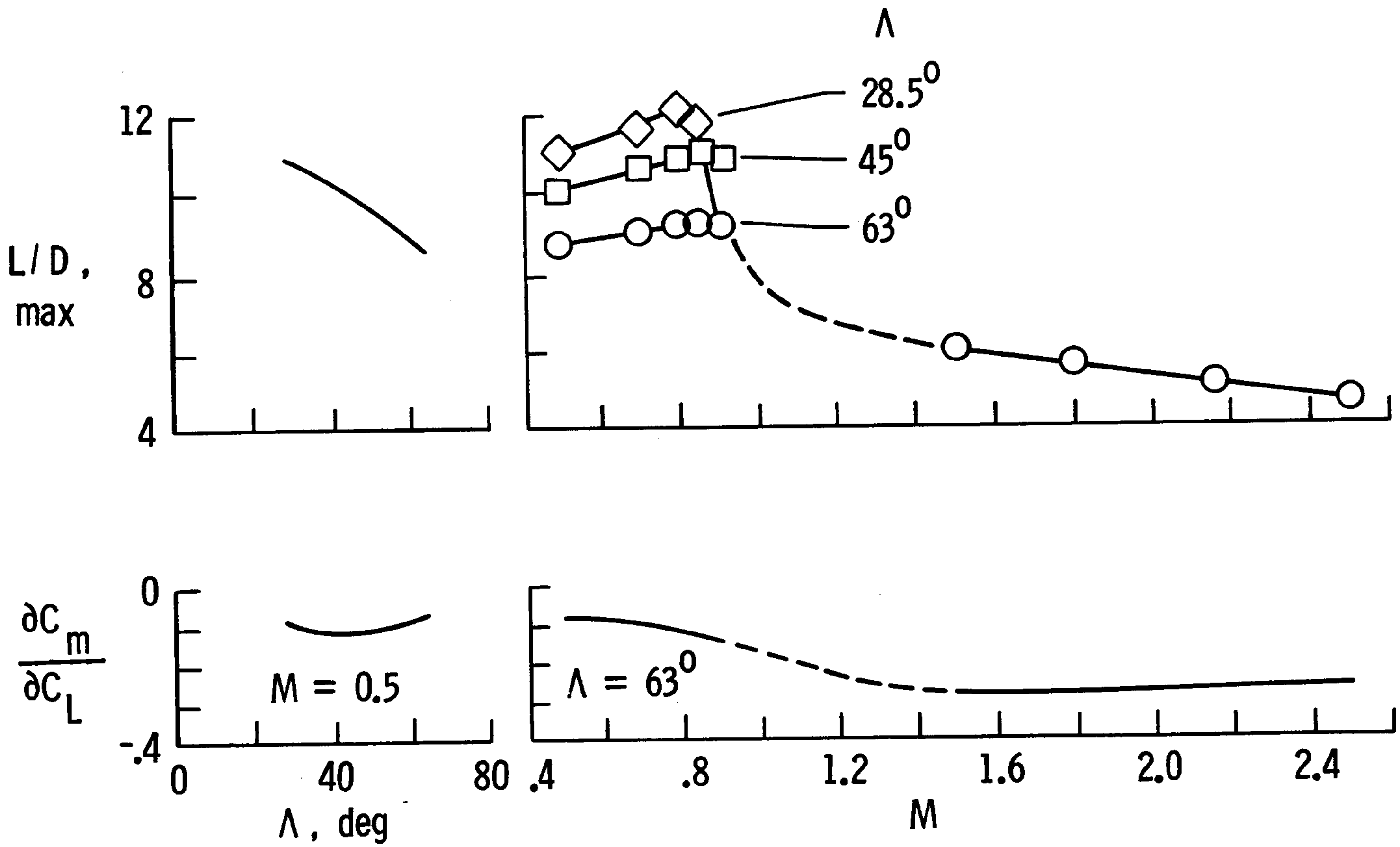


Figure 12.- Variable-sweep wing fighter characteristics.

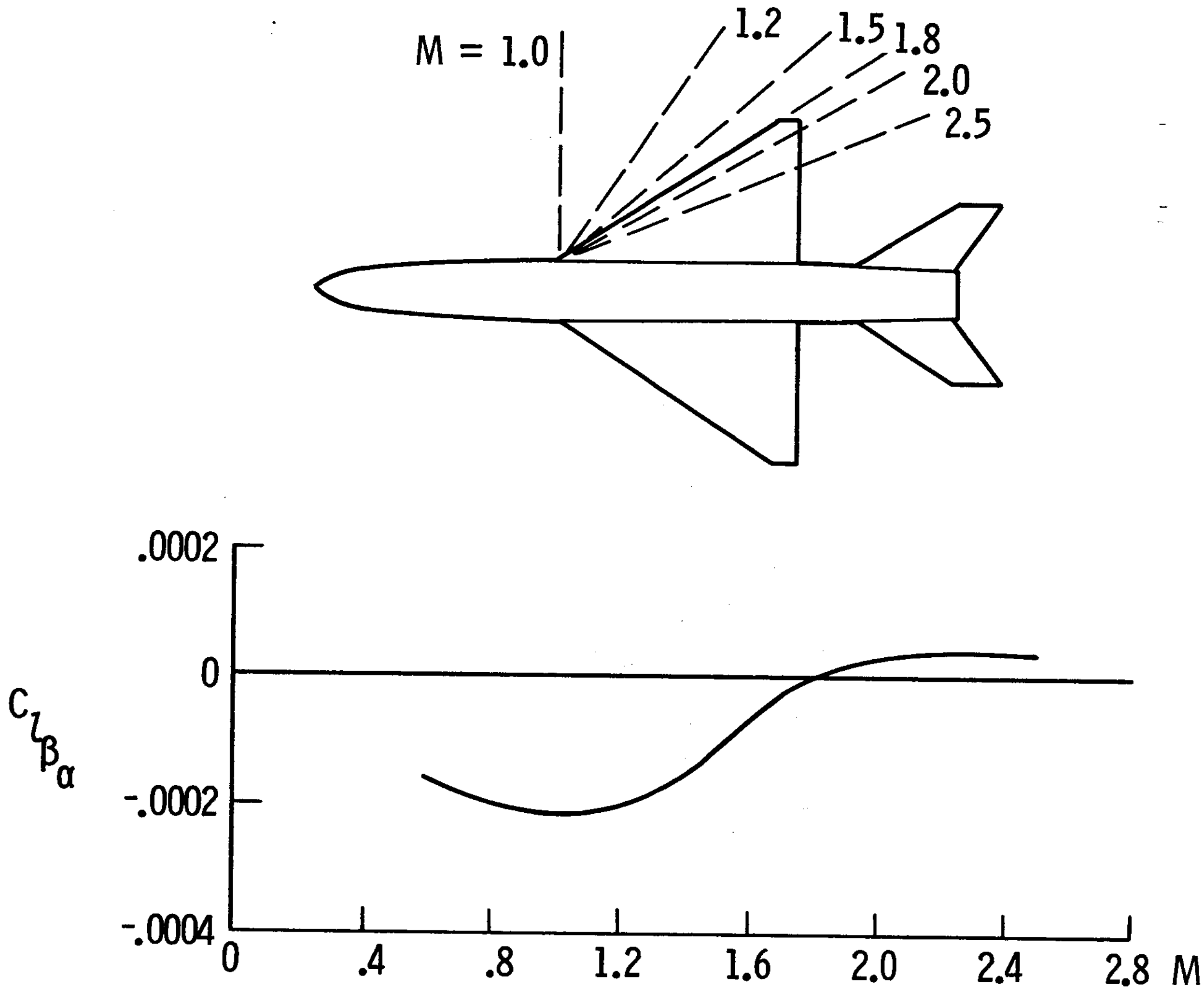


Figure 13.- Delta wing fighter lateral characteristics.

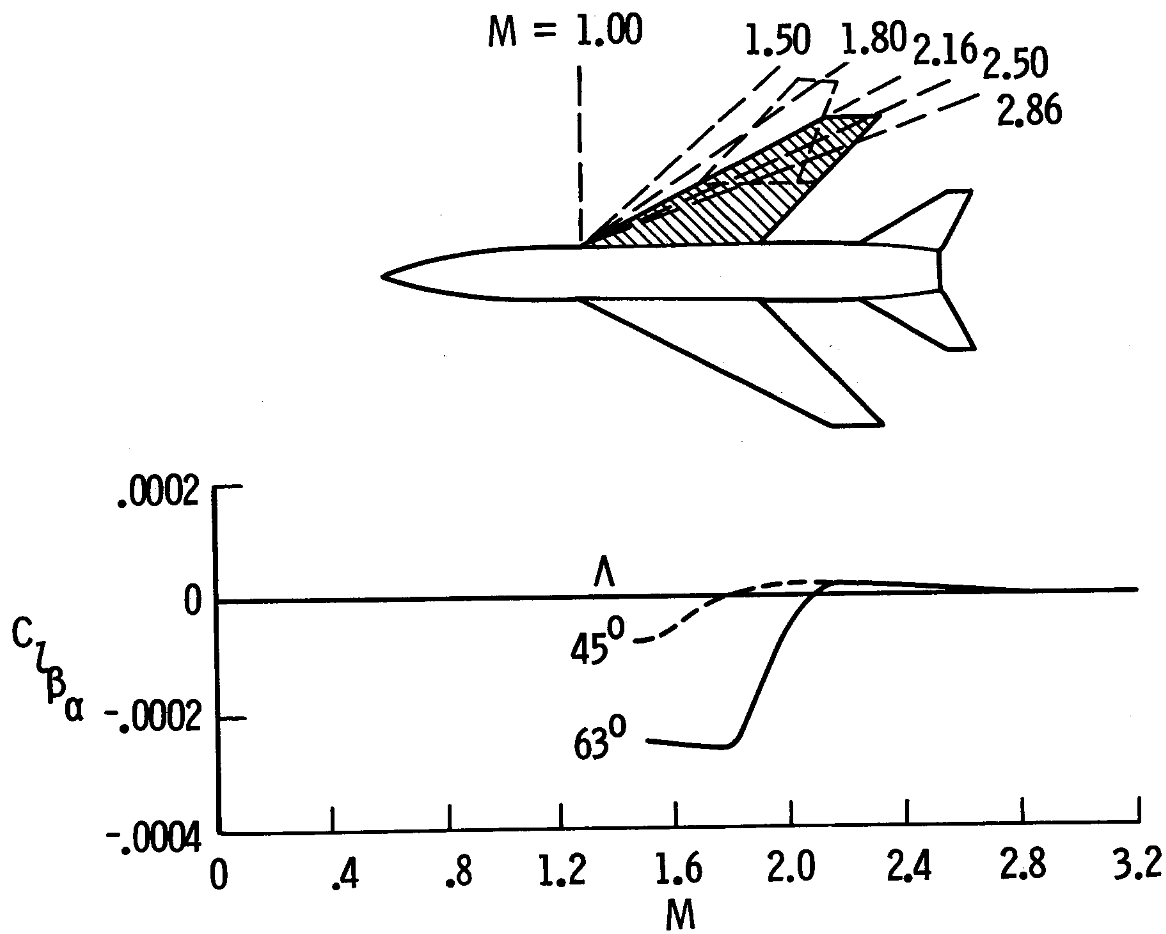


Figure 14.- Swept wing fighter lateral characteristics.

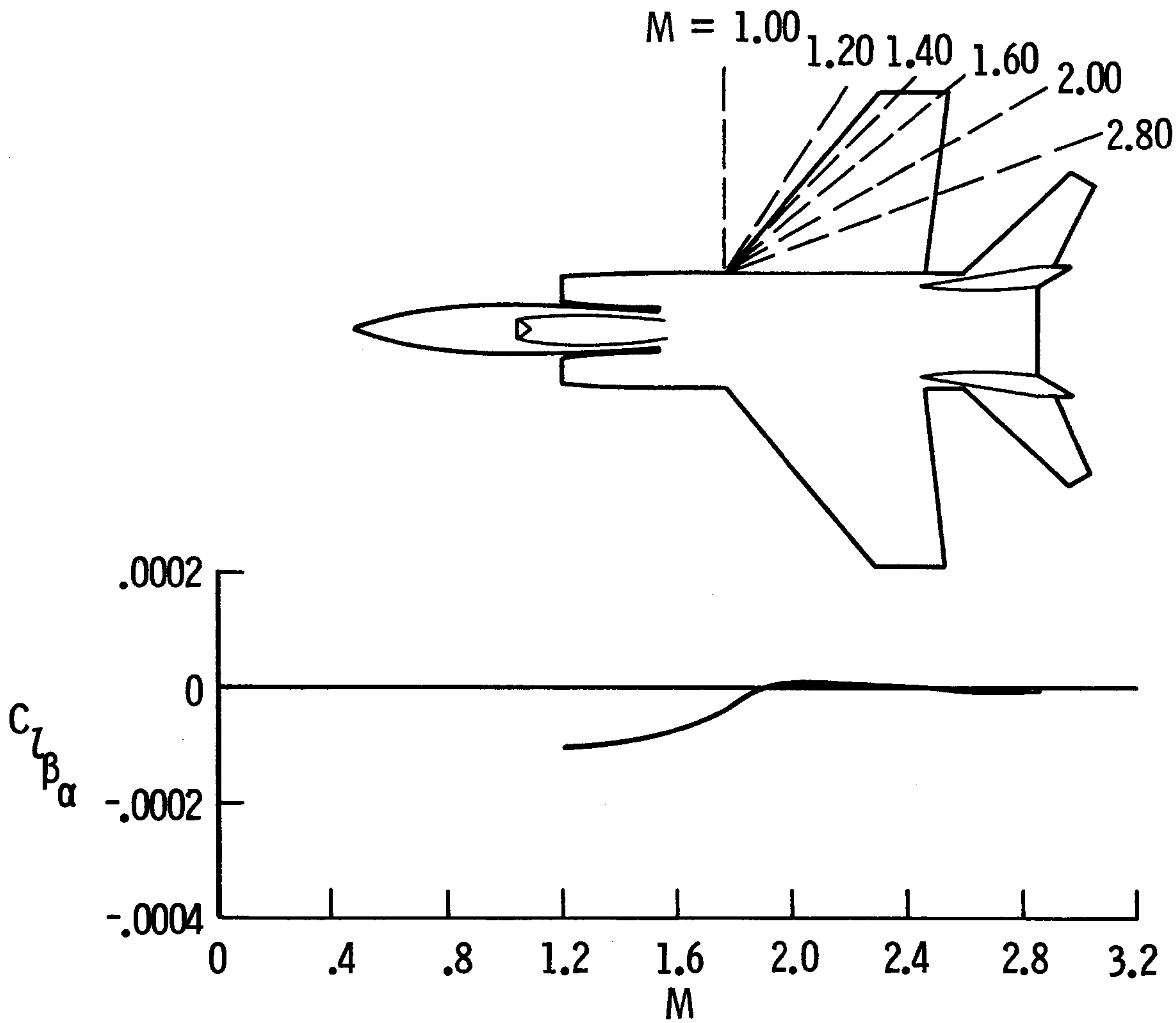


Figure 15.- Trapezoidal wing fighter lateral characteristics.

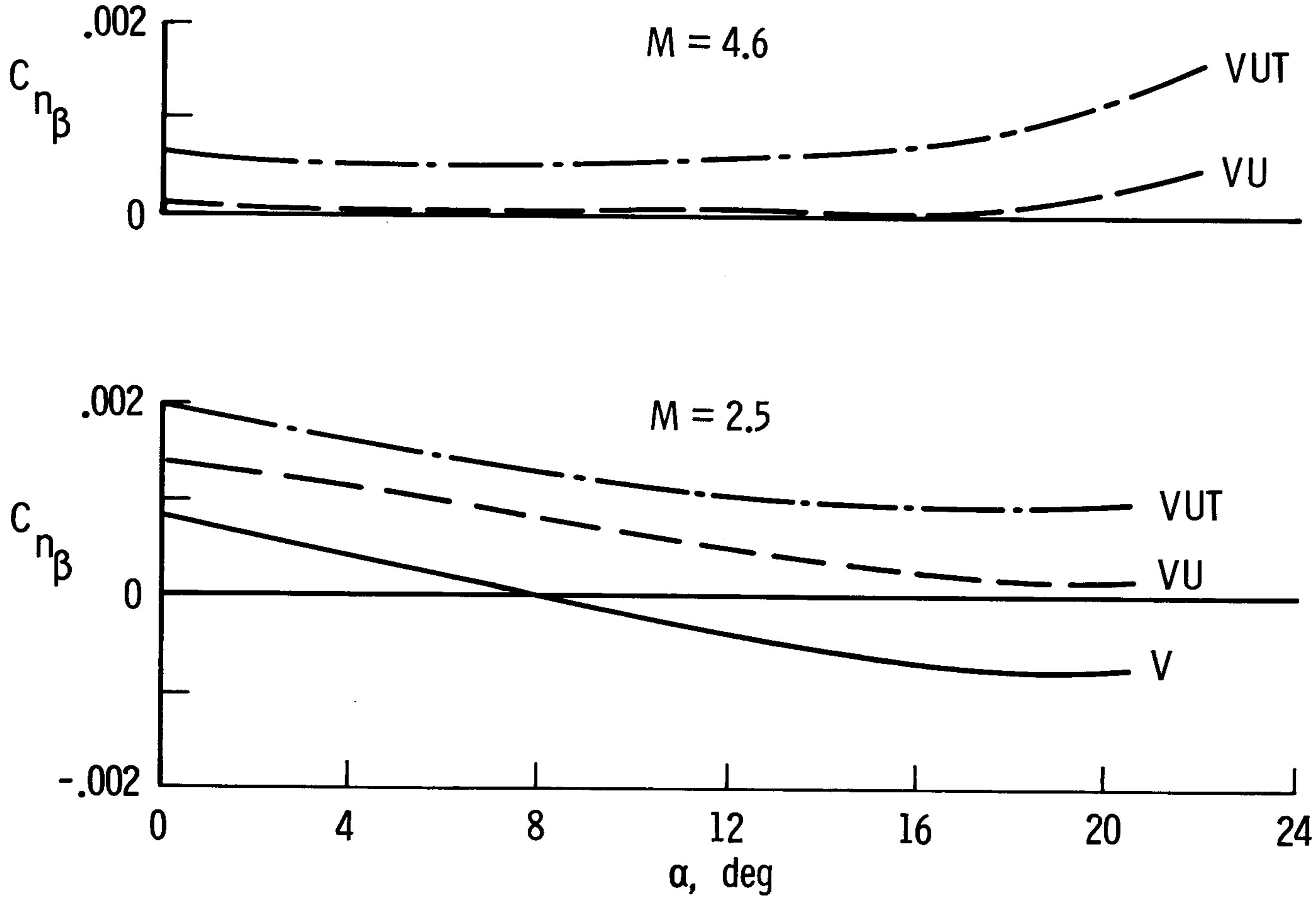
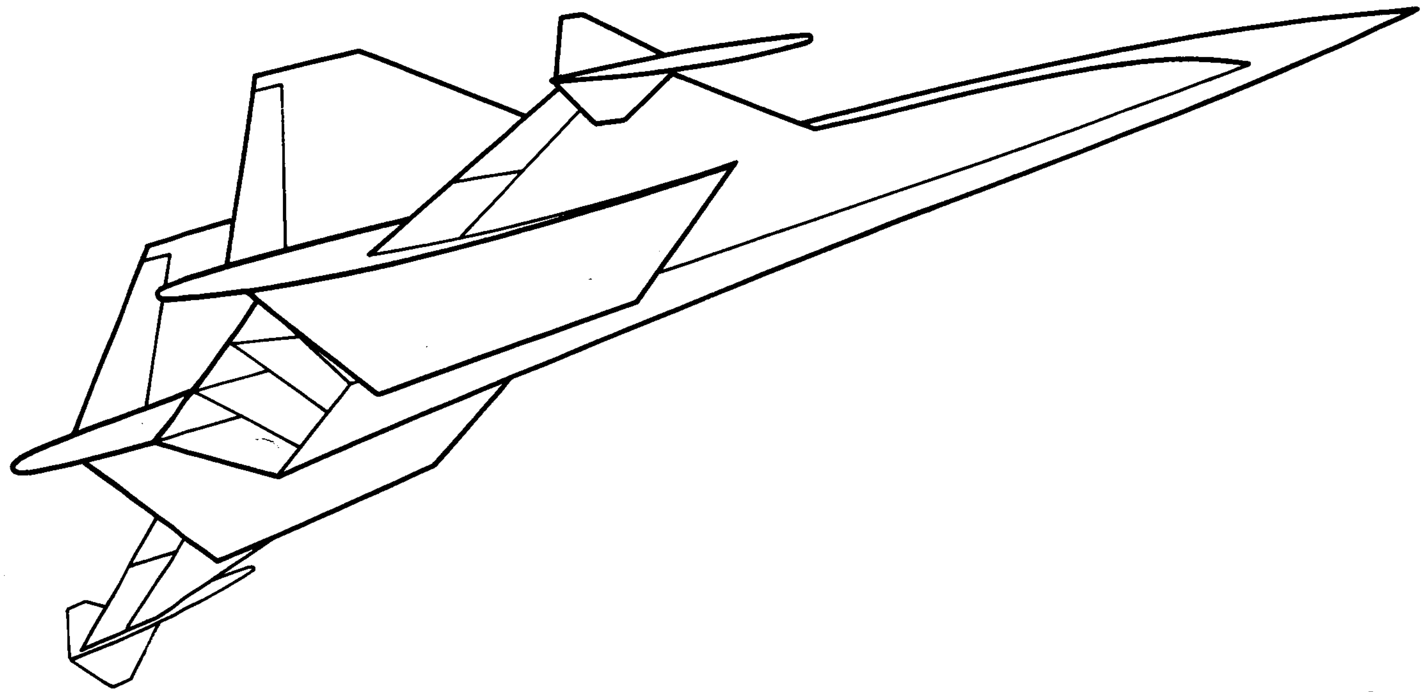


Figure 16.- Trapezoidal wing fighter directional characteristics.



THE MOST IMMEDIATE PROSPECT FOR AERODYNAMIC APPARATUSES IS TO ATTAIN HYPERSONIC SPEEDS, THAT IS, SPEEDS APPROXIMATELY 5 TIMES AS FAST AS THE SPEED OF SOUND.

I. ANUREYEV - 1970

Figure 17.- Soviet fighter technology.

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15. Supplementary Notes

16. Abstract

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